

TELESCOPES VERSUS MICROSCOPES: THE PUZZLE OF IRON-60

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Abstract. The discovery that the short-lived radionuclide ^{60}Fe was present in the oldest meteorites suggests that the formation of the Earth closely followed the death of a massive star. I discuss three astrophysical origins: winds from an AGB star, injection of supernova ejecta into circumstellar disks, and induced star formation on the boundaries of HII regions. I show that the first two fail to match the solar system ^{60}Fe abundance in the vast majority of star forming systems. The cores and pillars on the edges of HII regions are spectacular but rare sites of star formation and larger clumps with masses $10^{3-4} M_{\odot}$ at tens of parsec from a supernova are a more likely birth environment for our Sun. I also examine γ -ray observations of ^{60}Fe decay and show that the Galactic background could account for the low end of the range of meteoritic measurements if the massive star formation rate was at least a factor of 2 higher 4.6 Gyr ago.

1 Introduction

The study of planet formation can be approached from two sides: the large scale encompassing the molecular core that collapses to a star and surrounding planetary disk, and the small scale in which the planets and the remnants of their formation, meteorites, are examined in detail to learn about the conditions of the early solar system (ESS).

Astronomers have identified each of the main stages by which the interstellar medium (ISM) becomes molecular, fragments, and individual cores collapse to protostars. We have imaged the disks of planet forming material around young stars and witnessed the debris from planetesimal collisions. Although many details remain to be worked out, the basic properties of a proto-planetary disk, such as mass, size, composition, and lifetime, are well characterized. We have also identified over 200 extrasolar planetary systems around nearby stars. The surprising

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diversity of these systems, however, raises the vexing issue of how typical is our solar system.

Cosmochemists have identified the oldest rocks in the solar system and determined their age, 4.567 Gyr, to astonishing precision. Careful study of their mineralogy shows the detailed conditions, including, for example, thermal history, radiation field, and transport processes, in the ESS. As with cosmologists studying the Universe, however, there is one and only one system at hand which raises the vexing issue of how typical is our solar system.

The areas where these two different lines of inquiry, telescopic and microscopic, overlap provide interesting comparisons. Short lived radionuclides (SLR), with half-lives less than 3 Myr (see below), are of particular interest for understanding planet formation and the astrophysical environment of the ESS. In this chapter, I focus on the puzzle presented by the presence of ^{60}Fe in the most primitive meteorites. As I show, it may be hard to reconcile the astronomical and cosmochemical pictures but it is important to try since it may show the limitations in our knowledge or understanding and it may also help show whether our solar system is indeed typical, or not.

I begin by reviewing the astronomical and cosmochemical background to this subject. These sections are brief as they are covered in other chapters in this book. I discuss three different scenarios which have been proposed for the delivery of SLR into the ESS and assess the probability for incorporation of ^{60}Fe . I conclude that the only viable mechanism that might apply to a large number of planetary systems is the rapid collapse of large cluster forming clumps neighboring a massive star forming region. Finally I return to a basic assumption that the ^{60}Fe abundance is greater than the Galactic background and show a discrepancy between the predicted level and recent γ -ray observations.

2 Astronomical observations of star and planet formation

Stars form in molecular clouds, strung out along the spiral arms of the Galaxy. Our current understanding of the processes by which these large and massive clouds condense to stellar scales was recently summarized by McKee & Ostriker (2007). A rotationally supported disk inevitably accompanies the protostar due to conservation of angular momentum and the magnification of any initial spin. These disks initially funnel material onto the growing star but subsequently become the sites of planet formation. The observational properties and the theory behind the coagulation of sub-micron sized ISM dust grains to planetesimals are reviewed in the chapters by Hogerheijde and Youdin.

For the purposes of the discussion here it is important to note that several states, or phases, of gas coexist in the ISM (Cox 2005). The lowest density state is a hot ionized phase produced by supernovae and this fills most of the volume. Most of the mass is in atomic clouds at intermediate temperatures. The highest density state is cold and molecular. Most stars form in giant molecular clouds

with typical sizes¹, $L \approx 50 \text{ pc}$ and masses, $M \sim 10^5 M_\odot$. The clouds possess considerable substructure, generically characterized as clumps with sizes $L \approx 5 \text{ pc}$ and masses, $M \sim 10^3 M_\odot$ (Williams, Blitz, & McKee 2000). Individual stars form in dense cores within clumps, with typical radii $R \approx 0.05 \text{ pc}$ and mass $M \approx 1 M_\odot$ (di Francesco et al. 2007). Protostellar disks have radii $R \approx 100 \text{ AU}$ and masses ranging from $M \approx 10^{-3} - 10^{-1} M_\odot$ (Andrews & Williams 2007).

Although many observational and theoretical studies are directed toward the formation of isolated, individual stars, as this is the simplest system to understand, most stars form in large clusters (Lada & Lada 2003). The stellar mass distribution is heavily skewed toward the low end in terms of numbers but the few massive stars dominate the luminosity and their radiation, winds, and eventual supernovae may significantly affect the properties of neighboring primordial planetary systems.

The timescales are also critical for our comparison with cosmochemistry. It is surprisingly difficult to identify young or old clouds (or even tell the difference – see Williams & Maddalena 1996) and consequently the lifetimes of giant molecular cloud are highly uncertain. Current estimates, based on theories of cloud formation and destruction, range from $\approx 1 - 20 \text{ Myr}$ (Hartmann, Ballesteros-Paredes, & Bergin 2001; Matzner 2002). The evolutionary state of cores within star forming clouds are easier to characterize and several lines of evidence suggest that as soon as they become sufficiently dense, $n_{\text{H}_2} \sim 10^5 \text{ cm}^{-3}$, stars will rapidly form within a few free-fall timescales, $\sim 10^5 \text{ yr}$ (Jorgensen et al. 2007). The presence of a circumstellar disk around a star is most readily detected as a long wavelength excess above the stellar photosphere. Large surveys of clusters with different ages show that the fraction of stars with disks decreases from an initial value close to unity to zero by 6 Myr, and that the median disk lifetime is about 3 Myr (Haisch, Lada, & Lada 2001; Hernandez et al. 2008). This is the characteristic timescale for the formation of planetesimals although the last steps in the growth of fully fledged planets may take considerably longer (see chapters by Kalas and Beichmann).

3 Short lived radionuclides and the importance of ^{60}Fe

Astronomers are limited to studying the light that molecular cores, young stars, and dusty disks either emit naturally or absorb and scatter from a background or nearby source. Having rocks in the laboratory, however, allows for far more targeted and detailed investigations. Cosmochemists can break down individual grains within meteorites to the atomic level and measure their structure, mineralogy, and isotopic composition to learn about the precise conditions in which they formed.

An element can have unstable isotopes that are chemically identical but decay over cosmic timescales. A dust grain with a particular mineralogy can therefore be incorporated into a planetesimal but subsequently change its composition. These

¹I use \sim to indicate an order of magnitude variation around a value and \approx for a factor of 3.

isotopic anomalies are then frozen into the material and, unless the planetesimal undergoes further processing, are immutable. SLR, defined here as having half-lives less than the 3 Myr characteristic lifetime of disks, therefore provide a natural chronometer for planet formation. I refer the reader to the chapters by Aleon and Gounelle for more detail and the broader aspects of such work.

^{60}Fe decays to ^{60}Ni with a half life of 1.5 Myr and its presence in the ESS was inferred by the correlation² of the isotope ratio, $^{60}\text{Ni}/^{61}\text{Ni}$, with the main isotope of iron, $^{56}\text{Fe}/^{61}\text{Ni}$ (Tachibana & Huss 2003). The exact abundance of ^{60}Fe in the ESS is not yet firmly established, with published measurements ranging from $[^{60}\text{Fe}]/[^{56}\text{Fe}] = 3 - 10 \times 10^{-7}$ (Tachibana et al. 2006; Moynier et al. 2005) but it appears to be greater than the expected background level.

The Galactic background is set by a balance between production in massive stellar winds and supernovae and destruction by radioactive decay. The equilibrium abundance of any radionuclide, normalized by the ratio of production rates, is then a simple function of its decay time (Schramm & Wasserburg 1970). Jacobsen (2005) plots the normalized abundances of many radionuclides with half-lives from 0.1 Myr to almost 10 Gyr against the expected background. Solar system levels are generally lower than the ISM average but most radionuclides with half-lives greater than 3 Myr fit a model with a slow exchange, over a ≈ 60 Myr timescale, between the hot ionized medium and cold, molecular clouds. The background level decreases rapidly with decay time and many SLR lie above this model, however.

The origin of radionuclides with abundances above the background can be broadly categorized in two ways: production by energetic particles from the active protosun and rapid transport from an external source into the ESS (Wadhwa et al. 2007). Both mechanisms have considerable flexibility and can be adjusted to match the abundances of most SLRs. Note that these are not mutually exclusive and both may have played a role. For instance, ^{10}Be can only be produced by spallation reactions, and is strong evidence for disk processing by protosolar radiation. On the other hand, the neutron rich iron isotope, ^{60}Fe , can only be formed in the cores of massive stars and must have then been delivered into the ESS on a timescale comparable to its half life.

The possibility of an external influence on the Sun's formation predates the discovery of ^{60}Fe (see Cameron & Truran 1977 and references therein) but the success of local irradiation models (e.g. Lee et al. 1998; see also the chapter by Gounelle in this volume) allowed most astronomers to downplay the issue. The importance of ^{60}Fe is that it is most clear-cut example of an SLR that could not have been produced by the protosun and therefore constitutes indisputable evidence that the products of nucleosynthesis from the core of massive star polluted the protosolar nebula. The puzzle of ^{60}Fe is that astrophysical contexts in which this occurs do not appear to be common. We are faced with either a significant gap in our understanding of star and planet formation or the realization that our solar system formed in a very unusual situation.

² If ^{60}Fe had not been present, the nickel ratio would have been independent of iron.

4 Possible origins of ^{60}Fe in the early solar system

4.1 Pollution of the protosolar nebula by an AGB star

Asymptotic Giant Branch (AGB) stars are evolved low and intermediate mass stars that have used up all the hydrogen in the central core and are now burning hydrogen and helium in shells around it. Mixing in these shells dredges up newly synthesized material from the core which may be blown out in a powerful stellar wind. In principle, SLRs with abundances comparable to ESS levels can be injected into the ISM through AGB winds (Cameron 1993). Figure 1 shows a wind-blown bubble from an evolved massive star in a star-forming molecular cloud; a simultaneous demonstration that this situation can occur but that its effect is limited to a very small region of the cloud.

In regard to the ^{60}Fe problem discussed here, its production in an AGB star requires faster reactions than that required for ^{26}Al . Wasserburg et al. (2006) show that only stars with masses $\gtrsim 5 M_{\odot}$ produce enough ^{60}Fe to match the ESS abundance. Stars with masses $> 10 M_{\odot}$ end their lives as supernovae and the possibility that they are the origin of the ^{60}Fe is discussed below. The stellar mass range of interest for the AGB hypothesis is therefore $5 - 10 M_{\odot}$.

By their nature, AGB stars have ages a little greater than the main sequence lifetime appropriate to their mass, $\sim 25 - 110 \text{ Myr}$ (Schaller et al. 1992). The molecular cloud in which they were born will have dispersed and any connection to ongoing star and planet formation will be serendipitous. Based on a census of the known mass-losing AGB stars and molecular clouds within 1 kpc of the sun, Kastner & Myers (1994) estimated the probability of a chance encounter to be $\sim 1\%$ per Myr. However, the ratio of AGB wind to molecular mass is very small, 3×10^{-4} , and they concluded – in the context of ^{26}Al – that the probability that the ESS was polluted in this way was $\leq 3 \times 10^{-6}$.

The Kastner & Myers work is an often cited argument against an AGB stellar origin for ^{26}Al in the ESS. The same reasoning applies to ^{60}Fe with an even lower likelihood due to the higher stellar masses necessary. Their result was based on the catalogs of AGB stars and molecular clouds in the solar neighborhood (1 kpc), however, and it is worth making a related but more general case for the entire Galaxy.

Jura & Kleinmann (1990) find that the average surface density of AGB stars with high mass loss rates is $\sim 10 \text{ kpc}^{-2}$, independent of Galactic radius. This implies a total population of about 3×10^3 in the Galaxy. Each lasts for about 1 Myr, a timescale comparable to the ^{60}Fe half-life, and ejects a total of about $3 M_{\odot}$ into the ISM. Based on the predicted wind SLR abundances, these winds can pollute about 100 times more mass to ESS levels or $\sim 10^6 M_{\odot}$ in total. The total molecular mass in the Galaxy is $1 \times 10^9 M_{\odot}$ (Williams & McKee 1997) so the proportion of star forming material that can be enriched is no more than 0.1%. This assumes that the star formation efficiency is independent of the presence of an AGB star which is entirely consistent with observations. Note that this is a generous upper limit since it does not include the low likelihood that an AGB star

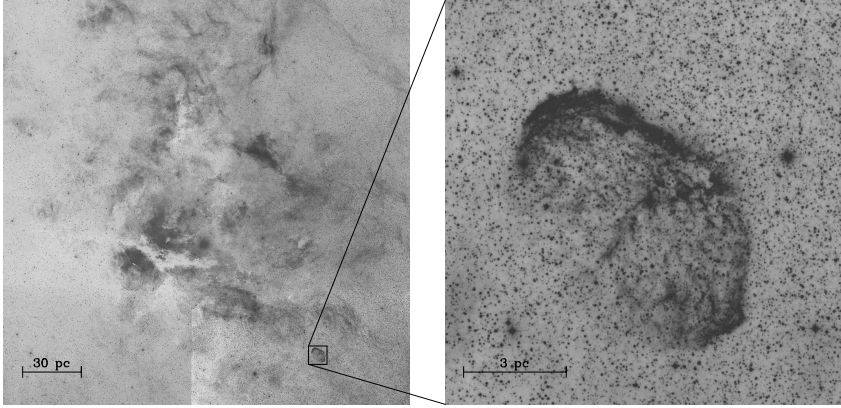


Fig. 1. The relative scale of AGB ejecta compared to molecular clouds. The two panels are from the Digitized Sky Survey and show optical extinction and nebulosity associated with the IC1318 star forming region in the left panel. The right panel shows a close-up of the wind-blown bubble from the AGB star, HD 192163. Note the relative scales that graphically demonstrates how small a part of a molecular cloud can be polluted by a massive star wind.

lie within or near a molecular cloud as in Kastner & Myers, nor does it include SLR decay during the (potentially $\gg 1$ Myr) passage from AGB wind to planetesimal. Finally the Jura & Kleinmann AGB number count likely includes many stars with masses too low to produce appreciable ^{60}Fe . Even without these additional factors, however, this simple calculation provides a robust and independent demonstration that the pollution of the proto-solar system by the winds from an AGB star is a very unlikely scenario for the origin of ^{60}Fe in the ESS.

4.2 Injection of supernova ejecta into the protoplanetary disk

Circumstellar disks can survive a supernova explosion as close as 0.2 pc and potentially capture significant levels of SLR from the ejecta (Chevalier 2000). Subsequent numerical simulations by Ouellette, Desch, & Hester (2007) show that solid grains can be efficiently mixed into the disk material. The mechanism works but how often does it occur?

A fundamental constraint is the similarity in the timescales for massive star and disk evolution (Figure 2). Even the most massive stars take 3 Myr to burn their hydrogen and evolve off the main sequence, at which point half of the disks around neighboring stars have disappeared. Further, only stars with masses greater than $30 M_{\odot}$ explode within 6 Myr, the maximum disk lifetime. Stars this massive are extremely rare and only found in the largest clusters.

An even stronger constraint comes matching the abundances of the supernova

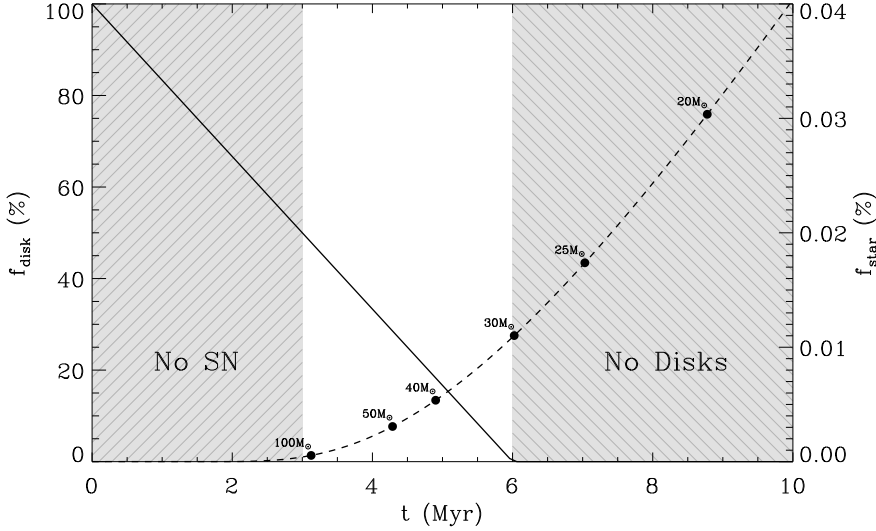


Fig. 2. Disk lifetimes versus main-sequence stellar timescales. The solid diagonal line decreasing from 100% to 0% represents the decrease in the disk fraction in clusters of varying age and is taken from Haisch et al. (2001). The curved dashed line plots the percentage of stars with main sequence lifetimes from 3 to 10 Myr. The hashed areas show that there are no supernovae before 3 Myr and no disks remain after 6 Myr. This leaves only a small range in time, 3 – 6 Myr, when there are both disks and a supernova. Moreover, only stars with masses greater than 30 Msun satisfy this constraint and they are extremely rare, numbering only about one in 10^4 stars.

ejecta with the meteoritic record. The amount of captured material is equal to the product of the disk area and the surface density of the supernova ejecta. The abundance of a particular SLR is therefore proportional to the supernova yield times the square of the ratio of the disk radius to the distance from the source. Ouellette et al. (2007) and Looney, Tobin, & Fields (2006) show this criterion requires the disk be within a “radioactivity distance” of 0.3 pc of a supernova with progenitor mass 10 – 40 Msun. This is only slightly greater than the survival distance. The disk injection scenario therefore only works over a very narrow range of distances and this makes it extremely unlikely.

In Williams & Gaidos (2007), we explicitly calculate the disk injection likelihood, taking into account the massive star lifetimes, disk evolution, and the constraints on distance from the source. We considered a cluster with N_* stars sampled from the initial mass function (IMF), $dN_*/dM_* \propto M_*^{-2.5}$ (Scalo 1986), and calculate the most likely supernova progenitor mass. This defines a supernova timescale and a corresponding disk fraction (see Figure 2). To take the disk-supernova distance into account, we model the cluster as expanding linearly with time and parameterize the expansion via the surface density at 3 Myr, an

observationally defined quantity. We also extended the enrichment range out to 0.4 pc to allow for more massive supernovae than considered by Ouellette et al. and Looney et al.

The results are shown in the left panel of Figure 3. The probability that a disk is injected peaks at 0.5 – 1.5%, depending on stellar density, at $N_* \simeq 10^4$. Small clusters are unlikely to harbor a supernova that explodes before all the disks have disappeared and most disks are too far from the supernova to be enriched in large clusters. In fact, the enrichment fraction is the dominant factor in the low overall probability; clusters with 10^4 stars have about a 50% chance of containing a high mass star that will become a supernova within 4 Myr implying a disk fraction of 1/3 at the time of the blast, but the cluster will be several parsecs in radius and only a few percent of disks will be close enough to the supernova to be enriched.

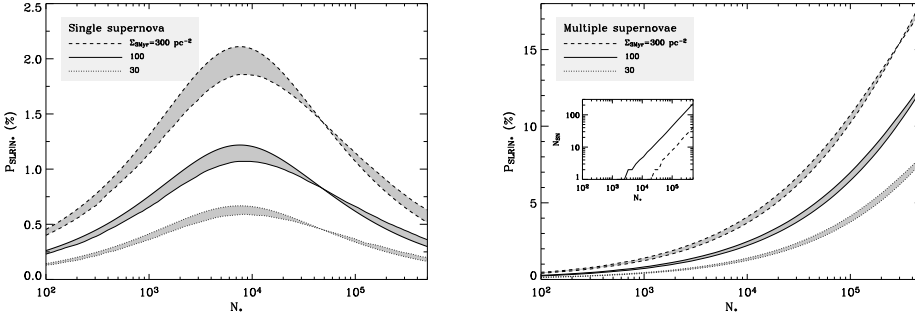


Fig. 3. Probability of enrichment of a protostellar disk by a supernova versus cluster size. In each panel three curves are plotted corresponding to different expansion rates, parameterized by the stellar number density, $\Sigma_{3\text{Myr}}$. The shading shows the range of probabilities over cluster formation timescales from 0 to 3 Myr. The left panel shows the disk enrichment likelihood for a single supernova event. Small clusters are unlikely to have a supernova before all disks have dissipated and most disks in large clusters are too far away from the supernova to be enriched to ESS levels. The right panel shows the disk enrichment probability in the case where multiple supernovae can enrich multiple disks. In this case, the probability rises strongly in large clusters where many supernovae occur (see inset) and many disks may be impacted.

It is also possible to relax an implicit assumption in the model that all the stars in the cluster form at once. This does not greatly change the disk injection probability. The greyscale associated with each surface density in Figure 3 shows the range of probabilities for a cluster formation timescale varying from 0 – 3 Myr. Except for the largest clusters, $N_* \gtrsim 10^5$ stars, the probability decreases with formation time since the rarer, massive stars will likely form after many low mass stars and their disks will have an evolutionary head start. This is for an unbiased sampling of the IMF. The probability can be increased by putting in a bias toward

forming high mass stars first (equivalent to shifting the stellar curve leftward in Figure 2, but there is no observational evidence for this. Young high mass stars are always surrounded by many low mass stars and no O star has been observed in isolation at less than 1 Myr.

Large clusters can host many supernovae and these can enrich multiple disks. In this case, and generously assuming that the low and high mass stars are spatially mixed³, the right panel in Figure 3 shows that the disk injection probability rises substantially to $\approx 10\%$ in the largest known clusters, $N_* = 5 \times 10^5$. However, most stars form in smaller clusters (actually an equal number per logarithmic bin) and the overall disk injection probability, for any given star in the Galaxy, is very small, $\lesssim 1\%$. Nevertheless, this shows that if the proto-solar system disk was impacted by a supernova blast, it most likely happened in an enormous cluster, similar in size or greater than W49 or η Carinae today.

This simple model can be expanded in a number of ways but it is hard to escape the fact that very few disks are enriched with SLR by direct incorporation of supernova ejecta. Gounelle & Meibom (2008) include an additional factor to allow for external photoevaporation of the disk by massive stars in the above formalism. This reduces the disk injection probability further, particularly in the most massive clusters where it negates the effect of multiple supernovae. Certainly massive stars can rapidly erode the outer parts of disks, as observed in the Trapezium Cluster in Orion (O’dell & Wen 1993) but it is not yet clear that this prevents planet formation in the inner parts. Indeed Throop & Bally (2005) postulate that the preferential removal of gas might enhance dust sedimentation and speed up the growth of planetesimals. Williams, Andrews, & Wilner (2005) show that enough mass remains in several Trapezium Cluster disks to form solar system scale architectures but more observations are required to show the statistics and significance of photoevaporation on disk mass (Mann & Williams, in prep). On the other hand, mid-infrared observations by Balog et al. (2007) and Hernandez et al. (2008) show marginally significant evidence for a decrease in the inner disk fraction of about a factor of 2 within 0.5 pc of massive stars.

Our model shows that the disk injection probability increases for higher cluster surface densities. We bracketed a range, $\Sigma_* \simeq 30 - 300 \text{ stars pc}^{-2}$, that is observed in infrared surveys (Adams et al. 2006, Carpenter et al. 2000). This is also consistent with Lada & Lada (2003) who show that the number of detectable clusters declines with age and estimate that only about 10% survive as recognizable entities beyond 10 Myr (i.e. with surface densities significantly above the field star background). Our Sun could not have formed in a long-lived cluster, however, because the solar system would have been disrupted by stellar encounters (Adams & Laughlin 2001).

Finally, we have treated supernova ejecta as isotropic but observations show a great deal of inhomogeneity (e.g. Hwang et al. 2004). In principle, this allows disk enrichment at greater distances but the overall disk injection probability decreases

³ In practice, high mass stars tend to lie together at the cluster center and their combined impact on the other stars is reduced.

because more disks nearby are not enriched. Specifically, let the filling factor be f . Then the ejecta are spread over an area $4\pi d^2 f$ at distance d from the supernova. Compared to the homogeneous case, a disk can be enriched at a greater distance, $\propto f^{-1/2}$, but the disks are distributed isotopically and the number that are impacted decreases linearly with f . The overall number of injected disks is the product of these and therefore proportional to $f^{1/2} < 1$. Consider the extreme case where all the ejecta are shot out in a single beam; at most one disk may be enriched very far from the star but all the other disks in the cluster are not enriched at all.

There does not appear to be any way to make this mechanism apply in a general way and I therefore conclude that the direct injection of supernova ejecta into the proto-solar system disk is an unlikely scenario for the origin of ^{60}Fe in the ESS.

4.3 Induced star formation

The fundamental puzzle of ^{60}Fe is that it associates the birth of our Sun with the death of a massive star. Yet stellar evolutionary timescales are generally much longer than formation timescales. Even the most massive stars, with the shortest lives, require 3 Myr before becoming a supernova and ejecting SLR into their surroundings. This is much greater than the < 1 Myr timescale for a dense core to form and collapse to a protostar.

As shown above, the timescale problem is one of the factors in the low likelihood of AGB wind contamination of the proto-solar system or direct injection of supernova ejecta into the proto-planetary disk. This problem would be mitigated, however, if there were a causal relation between the death of a massive star and the birth of lower mass stars. This led to the idea of induced star formation as a solution to the SLR problem.

It has long been known that large stellar associations in molecular clouds often consist of spatially and kinematically distinct subgroups ordered in age (Blauuw 1964). The canonical example is the four Orion groups, OB1a–d, spaced sequentially from north to south and with ages from ≈ 10 to ≈ 1 Myr respectively. Elmegreen & Lada (1977) proposed that such sequences could be explained by the induced collapse of molecular gas on the boundary of an expanding HII region.

There is a large body of literature on the observations and theory of star formation on the boundaries of HII regions (e.g., see the recent conference proceedings by Elmegreen & Palous 2007) and clearly some stars are induced. Hester & Desch (2005) have advocated that our Sun formed in this manner and incorporated SLR from the massive stellar winds and subsequent supernovae. As with the other SLR transport mechanisms, however, the essential question is not whether this might occur but how likely is it? The answer depends on the size scale involved.

Core scales, $L < 0.1$ pc

The expansion and photoionization of an HII region sweeps away the inter-clump material in a molecular cloud and reveals the denser regions. Indeed part of the reason why images of star formation on the boundaries of HII regions are so spectacular is because fingers of dusty, molecular gas are dramatically silhouetted against a bright background (e.g., Hester et al. 1996; Smith, Stassun, & Bally 2005). However, these structures amount to only a small fraction of the total mass of molecular gas in the cloud, are very short-lived, and they do not appear to have a significantly enhanced star formation efficiency. For instance, the famous “pillars of creation” in M16 have a total mass $M_{\text{gas}} = 200 M_{\odot}$ (White et al. 1999) and their high velocity gradients indicate dynamical timescales $\sim 10^5$ yr (Pound 1998). Only 11 of the 73 globules within the pillars contain a young stellar object (McCaughrean & Andersen 2002) which indicates a star forming efficiency, $M_*/M_{\text{gas}} \approx 3\%$, similar to molecular clouds in general and a total number of induced stars that is dwarfed by the $\approx 10^4$ stars in the host HII region (Hillenbrand et al. 1993).

Even if there were 100 such star-forming pillars at the cloud interface over the lifetime of the HII region, the total number of stars that were induced to form would amount to only about 10% of the stars in the central cluster. Obviously this is an extremely rough estimate but new high quality infrared and optical archival datasets should allow a more precise accounting of the amount of stars that are induced versus those that form spontaneously, and those in the associated HII regions.

As with the other SLR transport mechanisms, the geometric dilution of SLR as they travel from source to planetesimal is the strongest constraint. Looney et al. (2006) show that the radioactivity distance that matches the ^{60}Fe abundance with the ESS is about 100 times the core radius. For a typical core with radius ≈ 0.05 pc this corresponds to ≈ 5 pc. Note also that this assumes 100% transport efficiency from the supernova to the collapsing core which is likely to be overestimated by an order of magnitude (Vanhala & Boss 2002). A 10% efficiency would imply a supernova-core distance of ≈ 2 pc.

The M16 pillars are about 2 pc from the ionizing star so appear to be an ideal analog for the solar birthplace (Hester & Desch 2005). However, HII regions expand rapidly to tens of parsecs in size and any molecular cores or circumstellar disks must survive the direct impact of stellar wind and radiation for at least 3 Myr until the supernova occurs. Numerical simulations by Mellema et al. (2006) show that most molecular globules at the center of an HII region are photoablated within 0.4 Myr. Freyer, Hensler, & Yorke (2003) include the effect of stellar winds and show that they sweep away molecular filaments inside the HII region to beyond 10 pc by 3 Myr.

The impact on a stellar wind on a core and whether it might trigger star formation was studied by Foster & Boss (1996). They found that the core could be induced to collapse if it remained isothermal (i.e., radiates away the impact energy) during the passage of the shock and that this occurs only for speeds less than 100 km s^{-1} . Stellar winds are much faster than this and their impact will

shred a core. A simple visual comparison of their simulations with images of molecular globules inside HII regions look closer to the fast shock case suggesting that the dominant effect is core destruction and not star formation (Figure 4),

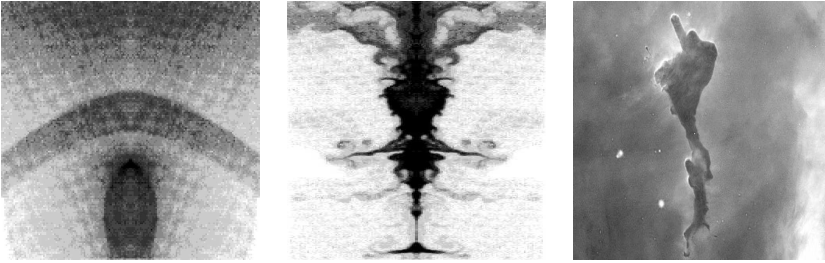


Fig. 4. Comparison of numerical simulations of induced core collapse with observations. The left two panels show results from Foster & Boss (1996) on the density distribution of dense cores impacted by slow and fast stellar ejecta. Speeds greater than 100 km s^{-1} shred cores rather than induce them to collapse. The right panel shows an image of the Keyhole nebula in the η Carina nebula. This is a dense core that appears to be in the process of being destroyed by the HII region rather than compressed to form new stars.

Observations of the molecular gas toward HII regions with Myr ages often show a ring of enhanced column density on the boundary with the cloud but very little if any molecular material in the center (e.g., Lang et al. 2000). Individual stars in clusters have an age spread of $\approx 1 \text{ Myr}$ but even if some stars were induced during the early expansion of the HII region their surrounding core has gone and any future supernova will, at most, impact a circumstellar disk. That is the scenario discussed above and shown to affect less than 1% of all protoplanetary systems. Since the evolution of the disk fraction includes observations of OB associations, any early induced star formation of this nature is implicitly taken into account.

Clump and cloud scales, $L > 0.1 \text{ pc}$

Larger targets capture more ejecta and can be further from the supernova. On the scales that characterize clumps and clouds, the radioactivity distance ranges from $50 - 10^4 \text{ pc}$ and better matches the sizes of evolved HII regions.

The issue here is that the large regions must collapse to stellar scales and there will be significant decay of ^{60}Fe as this happens. Larger regions have lower average densities and longer free-fall timescales. Using the size-linewidth relation in Heyer & Brunt (2004), and deriving a density from the virial mass, implies $t_{\text{ff}}(\text{Myr}) = 3.7L(\text{pc})^{0.41}$. The initial amount of ^{60}Fe must be higher to compensate for the decay and this reduces the clump-supernova distance by a factor $e^{t_{\text{ff}}/2t_{1/2}}$ where $t_{1/2} = 1.5 \text{ Myr}$ (Figure 5)⁴.

⁴Note that the free-fall timescale is much greater than the travel time for the ejecta to reach

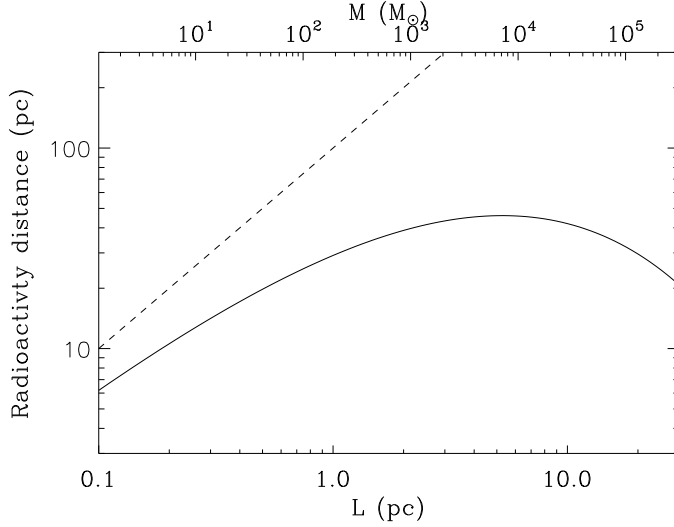


Fig. 5. The radioactivity distance at which an object of size L will receive ^{60}Fe to produce an abundance relative to ^{56}Fe that matches the ESS level. The dashed line shows the Looney et al. (2006) calculation with no decay and the solid curved line incorporates decay during the free-fall collapse.

The longer collapse times at large size scales offsets the greater amount of initial ^{60}Fe and the radioactivity distance has a maximum of 45 pc. Objects further away than this will be either too small to capture enough ^{60}Fe or too large to collapse before significant decay. However clumps with sizes $L = 2 - 11$ pc and masses $M = 10^3 - 4 \times 10^4 M_\odot$ that are within 40 pc of the massive stars and collapse as (or because) a supernova explodes could, in principle, produce numerous planetary systems enriched with ESS levels of ^{60}Fe . Of all the possibilities considered so far, these objects represent the most promising candidates to match the cosmochemical constraints on the birth environment of the solar system.

The case of the Rosette

The Rosette molecular cloud, with mass $2 \times 10^5 M_\odot$, sits adjacent to the well known Rosette nebula, a luminous 2–3 Myr old HII region powered by the NGC2244 cluster containing 7 O stars and about 10^4 stars in total (Townsley et al. 2003). The cloud contains several embedded clusters (Roman-Zuniga et al. 2008) indicative of ongoing star formation. Mid-infrared observations by Poulton et al. (2008) reveals circumstellar disks in the nebula in addition to protostars in the cloud (Figure 6).

There are 293 identified disks in the NGC2244 cluster and their detection

the source and the latter is therefore neglected.

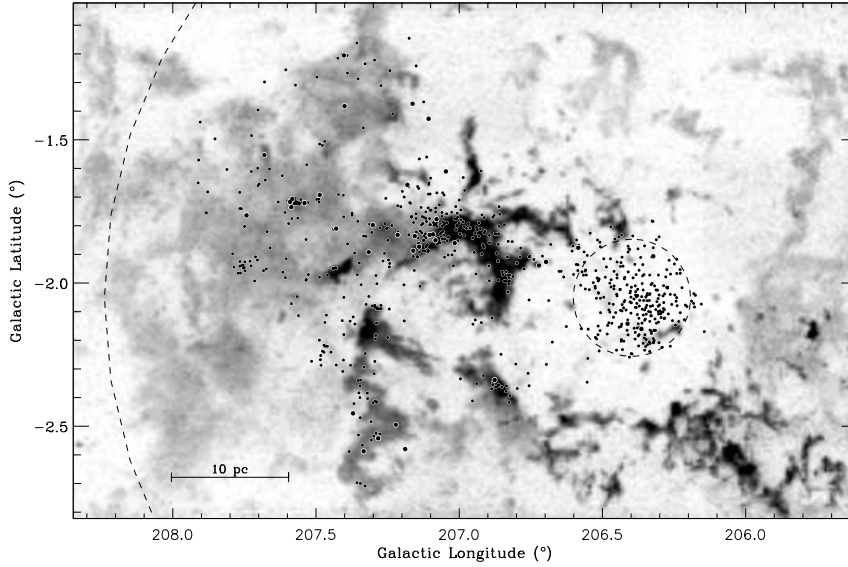


Fig. 6. Young stars in the Rosette molecular cloud. The greyscale plots CO emission from the cold gas in the cloud (Heyer, Williams, & Brunt 2006) and the dots show the location of stars with mid-infrared excesses (Poulton et al. 2008). These dusty sources form two distinct groups; a cluster of disks within the HII region remnants of its formation 2–3 Myr ago, and a distributed population of protostellar disks and envelopes in the cloud, concentrated toward the molecular peaks. The dashed lines show the 5 pc radius around the cluster at which dense cores could be enriched (if they survived) and the maximum 45 pc radioactivity distance at which clumps with size 5 pc could be enriched.

statistics are in proportion to that expected for its 2–3 Myr age (Balog et al. 2007). 458 sources lie in the cloud, mostly concentrated toward molecular peaks, and possess spectral energy distributions indicative of protostellar disks or envelopes and ages ≈ 1 Myr.

The HII region has evacuated a noticeable spherical cavity in the molecular gas with a radius of about 10 pc. However, the clear spatial segregation between the cluster and cloud sources suggest that the fraction of induced star formation at early times is small. If stars formed as the HII region expanded to its current size, we would expect dusty sources between the cluster and cloud. There are no identifiable cores within 5 pc of the cluster center. However, most of the cloud lies within the maximum radioactivity distance of 45 pc from the cluster and is structured into clumps with sizes and masses that match the conditions required for enrichment in Figure 5 (Williams, Blitz, & Stark 1995).

5 The Galactic background revisited

An essential point in the discovery of live ^{60}Fe in the ESS is that its abundance is above the expected Galactic background level. Recent γ -ray observations suggest they may not be so different, however. The measured flux of photons at the decay energy of an SLR can be directly converted to an abundance. Diehl et al. (2006) show that ^{26}Al is produced on a Galactic scale with an average abundance, $[^{26}\text{Al}]/[^{27}\text{Al}] = 8.4 \times 10^{-6}$, about one sixth the ESS value (Lee, Papanastassiou, & Wasserburg 1977). ^{60}Fe is less abundant and the line flux about ten times weaker but its decay has been detected and the inferred abundance, $[^{60}\text{Fe}]/[^{26}\text{Al}] = 0.23$ (Harris et al. 2005). This implies $[^{60}\text{Fe}]/[^{56}\text{Fe}] = [^{60}\text{Fe}]/[^{26}\text{Al}] \times [^{26}\text{Al}]/[^{27}\text{Al}] \times [^{27}\text{Al}]/[^{56}\text{Fe}] = 0.23 \times 8.4 \times 10^{-6} \times 0.092 = 1.8 \times 10^{-7}$ which is between one half to one sixth of the ESS values (Tachibana et al. 2006; Moynier et al. 2005).

Normalized by the production ratio, the observed abundances for both ^{26}Al and ^{60}Fe are both 1.5×10^{-3} . These are, respectively, a factor of 6 and 3 higher than the predicted ISM average (Jacobsen 2005). The reason for this discrepancy is not clear. Nevertheless, it seems hard to deny the γ -ray evidence and the implication that the observed ^{60}Fe background level may be within a factor of 2 of the low end of the range of meteoritic measurements, $[^{60}\text{Fe}]/[^{56}\text{Fe}] = 3 \times 10^{-7}$. Further, the Galactic star formation rate – and therefore the background – may have been about two times higher at the time the Sun was born (Rocha-Pinto et al. 2000). The match between the numbers is tantalizing and, if they hold, the ^{60}Fe puzzle goes away.

Even the high end of the ^{60}Fe abundance measurements, $[^{60}\text{Fe}]/[^{56}\text{Fe}] = 10^{-6}$, is only a factor of 3 greater than the enhanced, early Galactic background. Given the known inhomogeneity in the ^{26}Al emission (Knodlseder et al. 1999) might a potential explanation be that we formed in a “radioactive overdensity”?

The likelihood of being in an overdensity of 3 is no more than 1/3 if the new stars are uniformly distributed. In fact, young stars congregate in spiral arms close to the supernova that produce the background. However, the structure of the multiple phases of the ISM is complex and not well characterized (Cox 2005). The definitive answer will ultimately have to wait for higher resolution, higher sensitivity γ -ray observations but it may also be possible to address the issue via extragalactic observations of the ionized, atomic, and molecular gas components (e.g., Scoville et al. 2001; Calzetti et al. 2005; Schuster et al. 2007).

A crucial missing step is the journey from $\sim 10^7$ K hot ionized gas in supernovae remnants to ≈ 30 K circumstellar disk to planetesimal. There is some evidence for rapid cloud formation from atomic gas on Myr timescales (Hartmann et al. 2001; Elmegreen 2000) but there is no viable mechanism to convert the hot ionized medium to atomic gas on comparable timescales. Note that each delay of 1 Myr raises the required overdensity by a factor of 4 and 2 for ^{26}Al and ^{60}Fe respectively.

Finally, solving the ^{60}Fe conundrum in this way, results in the opposite problem of enormous excesses in the abundances of the longer lived radionuclides. This reflects the difficulty, as many studies have noted, of matching all the abundances of all the SLR from a single source (e.g., Harper 1996).

6 Discussion and Conclusions

I have critically evaluated several proposed mechanisms for the delivery of ^{60}Fe to the ESS and found that most are highly improbable. AGB stars have moved away from their birthsite and any cross-pollination of a molecular core or circumstellar disk would be serendipitous. Further, their output is too small to affect a significant fraction of the ISM. No more than 0.1%, and probably far less, of stars could receive ^{60}Fe in this way.

Supernova may inject SLR directly into disks but the range of distances over which disks both survive the blast and are enriched to ESS levels is very small. Further, few disks remain by the time of the supernova for all but the most massive, shortest-lived progenitors. In this case, I estimate that no more than about 1% of all protoplanetary systems could receive ^{60}Fe in this way.

I was unable to assign probabilities to induced star formation scenarios since the statistics are not well known. The population of young stars on the boundary of HII regions appears to be only a small fraction of that within the central cluster and the number that form deeper in the surrounding molecular cloud. HII regions expand rapidly and are tens of parsecs in size before any supernova explosion. Matching the required high levels of ^{60}Fe places individual star forming cores well within the boundary of mature HII regions and they would be shredded by stellar winds. Even if a core were to collapse and form a star, the surrounding envelope would be photoablated or swept away by the time of a supernova which would impact, at most, a circumstellar disk. This scenario is effectively the same as the direct disk injection hypothesis since that used a prescription for disk evolution that included observations of clusters with massive stars.

Larger, cluster forming clumps in the molecular cloud beyond the HII region can capture enough supernova material and collapse fast enough to deliver ESS levels of ^{60}Fe to planetary systems. The large scale “collect-and-collapse” scenario for molecular clumps neighboring a massive star forming region may be the most promising solution to the ^{60}Fe puzzle. Molecular clouds are found around many supernova remnants and, although they may be strongly disrupted, star formation can occur in the surviving gas (Huang & Thaddeus 1986; Reach & Rho 1999; Reynoso & Mangum 2001). Perhaps the Orion subgroups are an example where this happened in the past and the Rosette cloud an example where this will happen in the future. However, only through detailed surveys of the molecular and protostellar content in young cloud-supernova interactions that quantify the amount and efficiency of star formation can we assess the likelihood that the Sun was born in such an environment.

The discrepancy between the γ -ray measurements of the ^{26}Al and ^{60}Fe background with model calculations needs to be understood. Also, more sensitive cosmochemical measurements will reduce the uncertainty on the initial abundance of ^{60}Fe and constrain the timing of its injection (Bizzarro et al. 2007, Dauphas et al. 2008). If the high end of the current range is confirmed, the background can be ruled out as the source although it may be a significant component that reduces the amount required from a discrete source.

Finally, if there really is no common scenario that can deliver large amounts of ^{60}Fe from a massive stellar core to a protoplanetary system, we are faced with the prospect that our solar system may be a one-in-a-hundred rarity. Astronomers have a long history of rejecting the idea that we are special but what are the implications in this case?

It seems reasonable to assume that however ^{60}Fe was delivered to the ESS, many other SLR were incorporated in the same manner. But if this was an unusual occurrence, then most planetary systems have lower levels not just of ^{60}Fe but of other SLR, particularly ^{26}Al . The latter is the dominant heating source for planetesimals at early times (Hevey & Sanders 2006) and a reduced abundance would imply a different thermal history and, potentially, result in a higher water content of terrestrial planets (Desch & Leshin 2004; Gaidos, Raymond, & Williams 2008).

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